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Short Bunch Research At Brookhaven National Laboratory*

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Abstract. Research into the production and utilization of short electron bunches at Brookhaven National Laboratory is underway at the Source Development Laboratory (SDL) and Accelerator Test Facility (ATF). Projects planned for the SDL facility include a 210 MeV electron linac with a dipole chicane that is designed to produce 100 μm long bunches and a compact electron storage ring that will use superconducting RF to produce sub-millimeter bunches. The ATF has a 30-70 MeV linac that will serve as the injector for laser accelerators that will bunch the beam into micron-length bunches. Coherent transition and synchrotron radiation from the short bunches will be used for beam diagnostics and infrared experiments.

INTRODUCTION

Research into short bunches and coherent radiation has a long history at Brookhaven National Laboratory. In 1989, Williams, et. al. (1) published a paper describing an attempt to find a coherent enhancement to the infrared synchrotron radiation spectrum from the electrons in the National Synchrotron Light Source (NSLS) VUV storage ring where the bunch length is on the order of 30 cm. Based on the theoretical work of Michel (2), which predicted that the enhancement at wavelength λ would be proportional to the number of electrons in a cube of side λ , it was anticipated that coherent enhancement would be observed at wavelengths as short as 1 μm . This was not seen. After carefully calibrating the infrared spectrometer against a black body source, it was observed that the synchrotron radiation spectrum in the 30-400 μm wavelength range was perfectly described by incoherent emission theory.

By reexamining the Nodvick and Saxon theory (3) [which was previously derived by Schwinger (4)], Williams, et. al. showed that for Gaussian bunches, coherent enhancement is only seen at wavelengths on the order of the bunch length or greater. This can not be observed in the case of the 30 cm bunches in the VUV ring, because the shielding effects of the vacuum chamber suppress the radiation at

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such long wavelengths. The Williams work, although unsuccessful in its attempt to see coherent radiation, reintroduced the correct theory of coherent synchrotron radiation and provided the proper framework for future research. Hirschmugl, Sagurton, and Williams went on to extend the Nodvick and Saxon theory by examining the statistics of the coherent enhancement due to the finite number of electrons in the bunch (5).

Earlier, Schweizer, et. al. (6) at BESSY reported that they were unable to see a coherent enhancement to the synchrotron radiation spectrum although Yarwood, et. al. (7) at SRS reported inconclusively that they may have seen some enhancement. Nakazato, et. al. (8) realized that coherent radiation from linac beams would be easier to see because the bunch length in linacs is much shorter than in storage rings. They definitively observed coherent radiation at the Tohoku linac with wavelengths near 1 mm and obtained the expected N^2 dependence of the radiation intensity on the number of electrons in the bunch. Coherent radiation was then seen by Blum, Happek, and Sievers (9) at the Cornell linac who later also observed coherent transition and Cherenkov radiation from the linac beam (10).

Current short bunch research at Brookhaven is centered at the Source Development Laboratory (SDL) and the Accelerator Test Facility (ATF). The SDL, which is now under construction, has a 210 MeV, S-band electron linac that will be used to produce sub-millimeter length bunches by magnetic compression. The linac will be the injector for a small electron storage ring that will use superconducting RF to store millimeter bunches and will also supply the electrons for a UV free electron laser (FEL). The ATF has a 70 MeV, S-band electron linac that is used for a variety of FEL and advanced acceleration experiments. The advanced acceleration experiments that use the intense electric fields produced by a laser for acceleration bunch electron beams to a fraction of the laser's optical wavelength. The remainder of this paper will discuss the short bunch experiments planned for the SDL and ATF.

SOURCE DEVELOPMENT LABORATORY

The SDL is now being assembled and is expected to be completed in 1996. It has a four section, 210 MeV S-band electron linac built by Titan-Beta. Space has been provided to add a fifth linac section and a fourth modulator to upgrade the energy to 310 MeV. Electrons for the linac are supplied by a 4.5 MeV S-band RF gun. The gun has a copper photocathode that is stimulated by a frequency tripled titanium sapphire laser that can produce light pulses that can be from 150 fs to over 10 ns in length. The laser can produce two light pulses that are up to 5 ns apart and are mode-locked to the linac RF. The gun is designed to produce 6 ps, 1 nC bunches with a normalized emittance of 1 mm-mrad but shorter bunch lengths can be produced with increased emittance or lower charge. An early experiment will be an attempt to produce sub-picosecond bunches from the gun with transverse dimensions greater than longitudinal in order to look for bunch lengthening due to off-axis, transverse fields in the linac.

The research program at the SDL has three components — UV FEL, magnetic bunch compression, and storage ring bunch compression. The FEL project will use the 10 m long NISUS wiggler (11) to produce 80–300 nm radiation. Some of the FEL schemes that have been considered use magnetic compression to produce sub-picosecond bunches. The FELs will require a careful optimization of bunch length versus energy spread. The coherent radiation bunch length monitor that will be developed in the magnetic bunch compression research will be used for diagnostics in the FEL experiments.

Magnetic Bunch Compression

A four dipole chicane, shown in fig. 1, will be used to compress the 84 MeV electron bunches after the second section of the SDL linac. The two remaining sections of the linac can be used to accelerate the electrons to a final energy of 210 MeV. A PARMELA (12) calculation performed by Tor Raubenheimer from SLAC predicts that starting from an initial bunch length $\sigma_z=600\ \mu\text{m}$, 1 nC of charge can be compressed to a length $\sigma_z=100\ \mu\text{m}$. The results of the calculation are shown in fig. 2 and the specifications for the bunch compressor are listed in Table 1.

TABLE 1. Compressor Parameters

Electrons/Bunch	6×10^9
Bunches/Linac Pulse	2
Bunch Spacing	5 ns
Initial σ_z	600 μm
Final σ_z	100 μm
Compressor Energy	84 MeV
Dipole Field	0.462 T
Dipole Bend Radius	0.602 m
Horizontal Displacement	0.128 m

FIGURE 1. Plan view of dipole chicane used for magnetic bunch compression.

FIGURE 2. PARMELA calculation of bunch shape after compression.

The magnet string for the compressor was designed so that the dipoles can be operated at full field, at zero field, or anywhere in between. This permits linac operation at any degree of compression from zero to maximum. As the magnetic field is increased, the beam trajectory changes between the limiting cases shown in fig. 1. The pole and vacuum chamber must be wide enough to accommodate this. A phosphor screen will be placed at the maximum dispersion point, halfway through the compressor to measure the beam position, size, and energy spread.

The final bunch length of the electron beam will be determined from the spectrum of the transition radiation produced when the electrons strike a metal surface. Coherent synchrotron radiation from the motion of the electrons through a bending magnet can also be studied. The far infrared spectra will be measured in these experiments using a Michelson interferometer.

The coherent transition radiation from the short bunches will be used in a pump-probe study of the response of dielectric materials to electromagnetic stimulation. The apparatus for the experiment is illustrated in fig. 3. The experiment requires two electron bunches from the linac, 5 ns apart. The first electron bunch passes through the metal foil and emits transition radiation at right angles to the beam direction. The electrons then continue through the foil and strike the sample. Although this bunch stimulates the sample, the back-scattered radiation pulse, after traveling through the 180° delay line shown in the diagram, arrives too late to probe the response of the sample to the first bunch. However, by adjusting the length of the delay line to match the time difference between the electron bunches, the second bunch can strike the sample simultaneously with the radiation. The delay can then be varied to determine the response of the sample as a function of time after excitation. Time dependent properties of the scattered radiation such as intensity, polarization, angular distribution, and spectrum can be measured.

FIGURE 3. Schematic view of pump-probe experiment.

Storage Ring Coherent Radiation Source

Although short bunches can be easily produced in linacs, the difficulty in controlling the charge and energy of the electrons from one bunch to the next can be a disadvantage for some experiments. Storage rings, by continually circulating the same bunch, can be a much more stable source of radiation than linacs. The quiet spectrum available from incoherent synchrotron radiation has proven to be particularly useful for spectroscopy at wavelengths from the infrared to hard x-rays. The bunch length in a storage ring can be reduced from the cm dimensions commonly produced in existing rings to 1 mm or less by increasing the RF voltage and frequency, reducing the ring energy, or reducing the momentum compaction (13).

The SXLS phase I storage ring (14) has operated at Brookhaven National Laboratory at energies from 50–200 MeV. It has a circumference of 8.5 m and has stored currents up to 0.5 A in a single bunch and 0.75 A in six bunches. The main parameters of the ring are listed in Table 2.

TABLE 2. SXLS Phase I Storage Ring Parameters*

	Original	New
Maximum Energy	200	MeV
Circumference	8.5	9.66 m
RF Frequency	211	2856 MHz
Peak RF Voltage	50	1500 KV
Dipole Field	1.1	T
Dipole Bending Radius	0.604	m
Superperiods	2	
Horizontal Tune	1.41	
Vertical Tune	0.41	
Momentum Compaction	0.322	
Energy Loss/Turn	0.234	KeV
Longitudinal Damping Time	19	ms
Horizontal Damping Time	96	ms
Natural Emittance	59.2	nm-rad

*Data from reference (15).

FIGURE 4. Plan view of the modified SXLS storage ring.

By increasing the RF frequency from 211 to 2856 MHz and the peak RF voltage from 50 to 1500 MV/turn, it should be possible to achieve submillimeter bunch lengths in the SXLS ring (15). Although it is possible to supply the additional RF voltage with a conventional room temperature RF system, the use of a 5 cell, CEBAF style superconducting RF system (16) is under consideration because it appears to be less expensive. The ring circumference will be increased to 9.66 m to accommodate the superconducting cavity. Parameters of the superconducting RF system for operation at 150 MeV are listed in Table 3 and a diagram of the SXLS ring is shown in fig. 4.

TABLE 3. Superconducting RF Parameters

Energy	150 MeV
Energy Loss/Turn	74 eV
Average Beam Current	5 mA
RF Frequency	2856 MHz
Peak Cavity Voltage	1.5 MV
R_{SH}/Q	240 Ω
Q_0	10^9
Synchronous Phase	89.997 Degrees
Synchrotron Radiation Power	370 mW
Cavity Losses	4.69 W
Supplied Power	3.75 KW
Cavity Temperature	2 Kelvin

The minimum bunch length that can be achieved in an electron storage ring at a given current is determined by collective effects. These are hard to predict because the ring impedance is not well understood for short bunches. Indeed, observing the bunch lengthening instabilities and measuring the impedance are goals of this experiment. Table 4 lists the expected bunch length in the ring at three different cur-

rents that were obtained by assuming a broad band longitudinal coupling impedance $Z_L/n=10 \Omega$.

TABLE 4. Bunch Lengths in Storage Ring Coherent Radiation Source*

Energy (MeV)	Particles/Bunch	σ_z (mm)
100	1.82×10^6	0.34
150	1.10×10^7	0.31
200	4.14×10^7	0.32

*Data from reference (15).

ACCELERATOR TEST FACILITY

The ATF can produce 30–70 MeV electron beams from a two section S-band linac. Like the SDL, the ATF has a 4.5 MeV RF gun. The frequency multiplied YAG laser used to stimulate the photocathode produces pulses that are too long for short bunch experiments but techniques for compressing the laser pulse are being considered. The ATF linac supplies beams for a variety of free electron laser and laser accelerator experiments. The laser accelerators will bunch electrons to a fraction of an optical wavelength, thus producing the shortest electron bunches at Brookhaven.

Two laser acceleration experiments are in progress at the ATF. One of the experiments uses the inverse Cherenkov effect and the other uses an inverse FEL (IFEL) for acceleration. Both experiments are powered by a 10.6 μm wavelength CO₂ laser and are expected to bunch the electron beam to micron wavelengths. The IFEL will be discussed in the remainder of this paper.

Inverse Free Electron Laser Accelerator

Because the electric field of the laser light is transverse to the direction of polarization, it can not be used to accelerate a collinear electron beam. Instead of using cavities, as in an RF linac, to give the electromagnetic wave an axial electric field, the IFEL uses a wiggler magnet to impart a transverse component to the motion of the electrons, thereby allowing acceleration by the transverse field of the laser. The energy dispersion of the wiggler causes the accelerated electrons to form a bunch on the accelerating phase of the laser waveform.

The Brookhaven IFEL (17) uses a 47 cm long, 1.25 T pulsed wiggler and a 5 GW CO₂ laser to accelerate electrons from 45 to 51.4 MeV. The wiggler period increases from 2.74 to 3.02 cm to remain in synchrony with the electrons as their energy increases. The vacuum chamber is a hollow sapphire waveguide that carries the laser light in the direction of the electron beam. The parameters of the IFEL (18) are summarized in Table 5.

TABLE 5. IFEL Parameters

Injection Energy	45 MeV
Exit Energy	51.4 MeV
Mean Accelerating Field	13.6 MV/m
Nominal Current	5 mA
Electrons/Linac Bunch	6×10^9
Peak Current	100 A
$\Delta E/E$	$\pm 3 \times 10^{-3}$
Emittance	70 nm-rad
Beam Radius	0.3 mm
Wiggler Field	1.25 T
Wiggler Period	2.74–3.02 cm
Wiggler Gap	4 mm
Wiggler Length	47 cm
Laser Power	5 GW
Laser Wavelength	10.6 μm
Maximum Laser Field	2.15 GV/m

Fig. 5 shows the results of a 1-dimensional particle simulation of electron beam bunching by the IFEL. The calculation shows that 51% of the electrons are captured in the accelerating bucket within a $2 \mu\text{m}$ long bunch. These results assume that all of the light is carried in a single mode. The presence of other modes in the optical waveguide will reduce the capture efficiency and lengthen the bunch.

Following acceleration, the electrons will be directed through a spectrometer magnet for energy analysis. A slit will be used to separate the accelerated bunch from the unbunched background. A metal target will be used to generate transition radiation from the $2 \mu\text{m}$ bunch and a dispersive, near IR spectrometer will be used to study the radiation and determine the bunch length. If successful, this technique will be useful for studying bunching in advanced accelerators and FELs.

FIGURE 5. Distribution of bunched electrons along CO₂ laser wave. Data provided by Juan Gallardo.

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REFERENCES

1. Williams, G. P., Hirschmugl, C. J., Kneedler, E. M., Takacs, P. Z., Shleifer, M., Chabal, Y. J., and Hoffman, F. M., *Phys. Rev. Lett.* 62, 261-263 (1989).
2. Michel, F. C., *Phys. Rev. Lett.* 48, 580 (1982).
3. Nodvick, J. S., and Saxon, D. S., *Phys. Rev.* 96, 180 (1954).
4. Schwinger, J. S., "On Radiation by Electrons in a Betatron," unpublished (1945).
5. Hirschmugl, C. J., Sagurton, M., and Williams, G. P., *Phys. Rev. A* 44, 1316-1320 (1991).
6. Schweizer, E., Nagel, J., Braun, W., Lippert, E., and Bradshaw, A. M., *Nucl. Instrum. Methods Phys. Res., Sect A* 239, 630-634 (1985).
7. Yarwood, J., Shuttleworth, T., Hasted, J. B., and Nanba, T., *Nature* (London) 312, 742-744 (1984).
8. Nakazato, T., Oyamada, M., Niimura, N., Urasawa, S., Konno, O., Kagaya, A., Kato, R., Kamiyama, T., Torizuka, Y., Nanba, T., Kondo, Y., Shibata, Y., Ishi, K., Ohsaka, T., Ikezawa, M., *Phys. Rev. Lett.* 63, 1245-1248 (1989).
9. Blum, E. B., Happek, U., and Sievers, A. J., *Nucl. Instrum. Methods Phys. Res., Sect A* 307, 568-576 (1991).
10. Happek, U., Sievers, A. J., and Blum, E. B., *Phys. Rev. Lett.* 67, 2962-2965 (1991).
11. Quimby, D. C., Gottschalk, F. E., James, K. E., Robinson, K. E., Slater, J. M., and Valla, A. S., *Nucl. Instrum. Methods Phys. Res., Sect A* 285, 281-289 (1989).
12. Crandal, K., and Young, Y., Computer code PARMELA — Phase and Radial Motion in Electron Linear Accelerators, private communication.
13. Murphy, J. B., "Issues and State of the Art for e^+/e^- Storage Rings," these proceedings.
14. Murphy, J. B., Biscardi, R., Halama, H., Heese, R., Kramer, S., Nawrocky, R., and Krishnaswamy, J., *Proceedings of the Third European Particle Accelerator Conference*, Gif-sur-Yvette Cedex, France: Editions Frontiers, 1992, Vol. 1, pp. 212-214.
15. Murphy, J. B., and Krinsky, S., *Nucl. Instrum. Methods Phys. Res., Sect A* 346, 571-577 (1994).
16. Biscardi, R., Broome, W., Keane, J., Mortazavi, P., Wang, J.-M., private communication.
17. Fisher, A., Gallardo, J., Sandweiss, J., and van Steenberg, A., "Inverse Free Electron Laser Accelerator," BNL report 47974, presented at the Third Workshop on Advanced Accelerator Concepts, Port Jefferson, NY June 14-20, 1992.
18. Gallardo, J., private communication.

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